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Magnet Engineering and Test Results of the High Field Magnet R&D Program at BNL

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***Abstract*—The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) has been carrying out design, engineering, and technology development of high performance magnets for future accelerators. High Temperature Superconductors (HTS) play a major role in the BNL vision of a few high performance interaction region (IR) magnets that would be placed in a machine about ten years from now. This paper presents the engineering design of a "react and wind" Nb_3Sn magnet that will provide a 12 Tesla background field on HTS coils. In addition, the coil production tooling as well as the most recent 10-turn R&D coil test results will be discussed.**

***Index Terms*- Accelerators, common coil, HTS, interaction region, react and wind, superconducting magnets .**

I. INTRODUCTION

The design of a 12 T common coil prototype magnet is nearing completion at the Superconducting Magnet Division (SMD) of BNL. The magnet will generate a very strong field using two pairs of flat pattern "racetrack" style epoxy impregnated Nb_3Sn coils. It will produce a high background field for HTS coil and short sample conductor testing with quick turnaround. Furthermore, by being a truly high-powered magnet with usable beam aperture and not simply another robust coil test fixture, it will validate the present mechanical design for accelerator use.

This short prototype represents the culmination of knowledge and techniques developed from a successful 10-turn common coil R&D program which has been ongoing at BNL [1]. Newly developed manufacturing techniques include: winding, tie-down, and handling methods for very fragile cable to achieve dense and uniform packing without conductor damage, epoxy vacuum impregnating using steel cavity molds and by vacuum bagging, mold release methods, mold surface coatings, mold gate and sprue design, epoxy flow path design, exiting main lead/instrumentation lead stabilizing and vacuum sealing, Nb_3Sn lead splicing, fiberglass cloth cable insulating and epoxy reinforcing, voltage tap and spot heater installation, epoxy crack minimization, critical dimensional control (coil flatness, thickness, and twist), and safe but effective coil axial and transverse coil preloading.

Even though the coils and the aperture are rectangular, the yoke and shell O.D. remain circular. Therefore, a few basic tried-and-tested designs have been carried over from SSC style cosine-theta magnets such as the RHIC DX [2] and BNL LHC D2 [3] insertion dipoles. Such workhorse designs include laminated 16 ga (1.5 mm) stainless steel collars with spot welds and tapered keys, 16 ga magnet steel yoke laminations, machined circular end plates, coil ends restrained by the end plates and set screws, and seam welded stainless steel half-shells with backing strips. These "conservative" design features offer the additional benefit of efficient and economical transition to a production environment.

II. 12 T PROTOTYPE MAGNET – DESIGN FEATURES

The cross-section of the magnet straight section is shown in Fig. 1. Two pairs of 45-turn Nb_3Sn flat pattern coils are contained within rectangular Kawasaki KHMN30L high manganese stainless steel laminated collars, forming a rectangular open aperture of 40 mm (1.57 in) x 34cm (13.25 in). This aperture is completely unobstructed from end-to-end thereby providing space to conveniently insert and remove HTS test coil "cassettes" from either end of the magnet without disassembly. The laminated yoke is made from 16 ga (1.5 mm) ultra-low carbon magnet steel and is held in a tight pack by three 12.7 mm (0.5 in) diameter stainless steel tie rods per yoke half. These tie rods will also keep the end yoke laminations from buckling under the inward radial force of the outer shell.

The yoke mid-plane is normal to the collar key line. This arrangement allows effective control of yoke/collar fit in the high force direction. Two 25.4 mm (1 in) thick roll-formed stainless steel half shells are seam welded around the yoke at the mid-plane, with the aid of a longitudinal weld backing strip. Seam weld shrinkage forces the yoke against the collar. This shell radial thickness is chosen to limit the axial strain of the coil straight section to 0.3% [4] at full power. The collars are designed to utilize the same phosphor-bronze tapered keys used in the twin aperture LHC D2 insertion dipole magnet.

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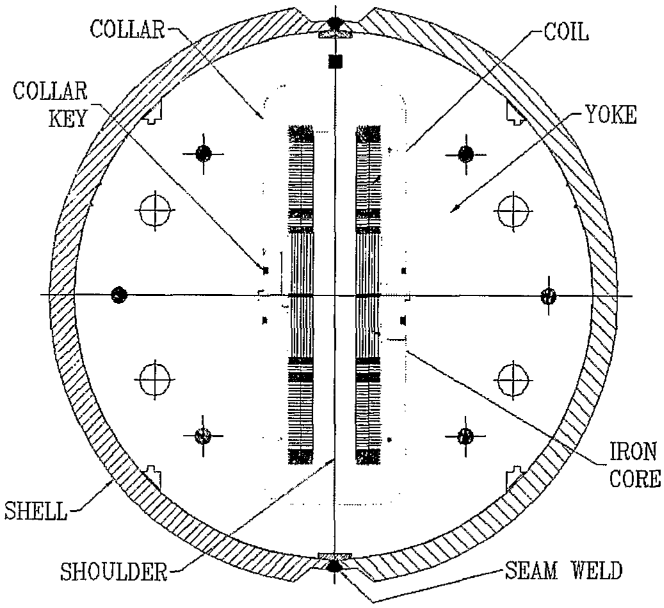

Fig. 1. 12 T magnet cross-section

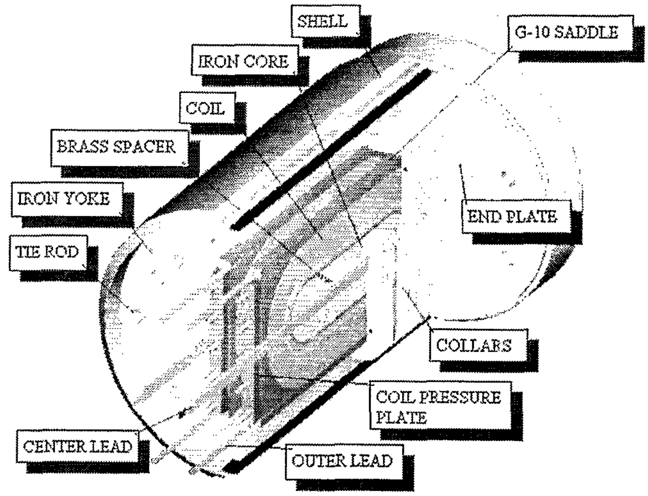

Fig. 2. 12 T magnet cut-away view

Stresses in the area of the collar key lugs are low. Analysis shows that with the structural rigidity of the massive yoke, the coil will deform less than .08mm (.003 in) the horizontal direction. The largest Lorentz force exerts a pressure of 75 MPa (10.8 kpsi), is in the horizontal direction. ANSYS finite element analyses indicate that this force is adequately contained by the solid web of the collar and the 12.7 mm (0.5 in) thick shell seam welds.

A cut-away view of the 12 T Prototype Magnet is shown in Fig. 2. The collars are pinned together into packs with stacking tubes. The coil ends are fitted with 25.4 mm (1.0 in) thick stainless steel pressure plates against which the set screws bear. These set screws (eighteen per end) are used to constrain the coil ends in the axial direction. They thread into a 127 mm (5 in) thick end plate. 3-D finite element analysis indicates that this thickness is necessary in order to maintain coil end deflection within 0.3% (0.45 mm) at a maximum axial Lorentz force of 1.1 MN (247,000 lbf). The end plate is circumferentially welded to the shell, thereby completing the magnet structure.

The four 45-turn Nb_3Sn coil assemblies are shown in Fig. 2. The cables are insulated with .05 mm thick x 12.7 mm wide dry fiberglass cloth using a half overlap wrapping scheme. The cable is wound around an inner spacer which is a 6.3 mm (.25 in) thick wound and mold-cured G-10 filament band. Fiberglass wrapped brass spacers, five turns thick, are located between cable turns four and five. The coil assembly including the machined outer G-10 saddle, and fiberglass cloth side reinforcement is vacuum impregnated and cured with the Composite Technology Development CTD-101 epoxy system, forming a strong, rigid, easy to handle unit. Tight cable packing and precise fitting of mating parts minimize voids filled with unreinforced epoxy [5].

Coils are then joined into pairs by splicing the inner lead "S-turns" to a straight stabilized exiting lead forming a perpendicular or "T" splice. The exiting center lead is used to vary the current between coil layers.

Laminations, made from the same material as the yoke, are precisely fitted inside the coils at the poles. These laminations form an iron "core" which is fastened firmly against the inside surface of the collars with stainless steel screws that engage special "keepers". The keepers are located within the collar packs at intervals along the length of the collared coil. Once collared, each coil pair is locked in position against shoulders located on the inside edge of the collar, and the iron core is held securely in place. Thus, the rectangular aperture is completely clear for test specimen insertion.

III. ANALYSIS

A. *Thermal Contraction and Modulus*

Specimens cut from the straight section of epoxy potted 10-turn coils were tested for elastic modulus at room temperature and for thermal contraction in the radial (vertical) direction at liquid helium temperature. Table I summarizes the results. The main conclusion based simply on $\sigma=E\varepsilon$ is that the warm assembly prestress in the vertical direction must be greater than or equal to 38 MPa (5540 psi) to ensure that the coils have a prestress greater than zero after cooldown.

B. *2-D Finite Element Analysis of the Cross-Section*

The magnet cross-section was modeled in 2-D using ANSYS primarily to understand the behavior of the collar. The applied coil horizontal load is 75 MPa (10.8 kpsi) over 45 turns. The half-shells are displaced 0.76 mm (.03 in) towards each other to simulate longitudinal seam weld shrinkage.

TABLE I
VERTICAL PRESTRESS CALCULATION SUMMARY[1]

	TC Strain (mm/mm)	TC Strain - Collar	Stack Height (mm)	Diff. Therm. Contr. (mm)
Steel Core	0.0019	0.0003	63.2	0.019
G-10 Spacer	0.0025	0.0009	6.8	0.006
5 Coil Turns	0.0043	0.0027	8.5	0.023
Brass Spacer	0.0038	0.0022	8.5	0.019
40 Coil Turns	0.0043	0.0027	68.1	0.184
G-10 Saddle	0.0025	0.0009	16.3	0.015
Sum				0.265
Prestress (MPa)				**38.2**

[1] E_{radial} = 11000 MPa (1.6x10^6 psi) @293K (measured).
$E_{longitudinal}$ = 6900 MPa (1.0x10^6 psi) @293K (measured).
T.C. $_{293K=>4K}$ (Collar) = .0016 cm/cm.

Frictionless sliding is permissible at all shell/yoke and yoke/collar interfaces. Horizontal displacement results at a 12 T central field are shown in Fig. 3.

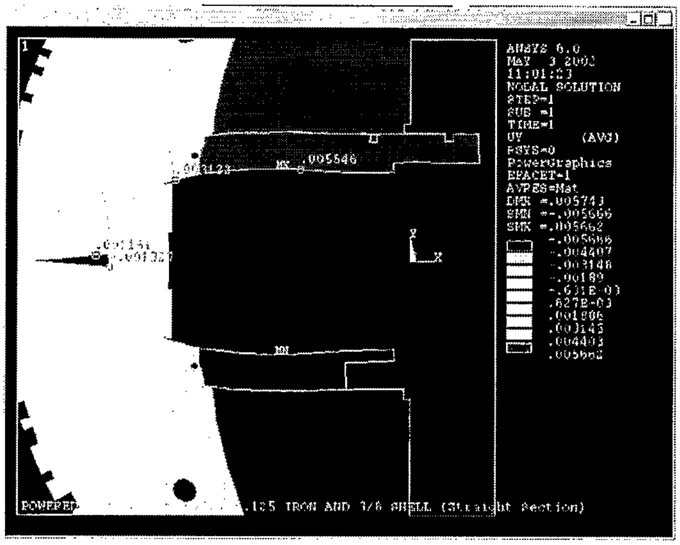

Fig. 3. ANSYS - collar horizontal deflection – inches (rot. 90° from figure 1)

The yoke midplane remains in contact near the shell but opens .05 mm (.002 in) adjacent to the collar. The collars spread apart .28 mm (.011 in) across the 40 mm aperture but uniformity in the coil region is within .08 mm (.003 in) The corresponding Von Mises Equivalent Stresses are acceptable, reaching 345 MPa (50 kpsi) at the inside corners of the 620 MPa (90 kpsi) yield strength collars.

C. 3-D Finite Element Analysis of the End Plate

The 127 mm thick Type 304 stainless steel end plate is designed to receive 1.1 MN axially through eighteen 19mm (.75 in) diameter set screws. The model includes the full rectangular cut-out for test coil insertion/removal. Fig. 4 summarizes the results. The axial deflection is within 0.4 mm (.016 in). The resulting stress profile is acceptable. The Von Mises Equivalent Stress does not exceed 330 MPa (48 kpsi). The yield strength of Type 304 stainless steel exceeds 480 MPa (70 kpsi) at helium temperature.

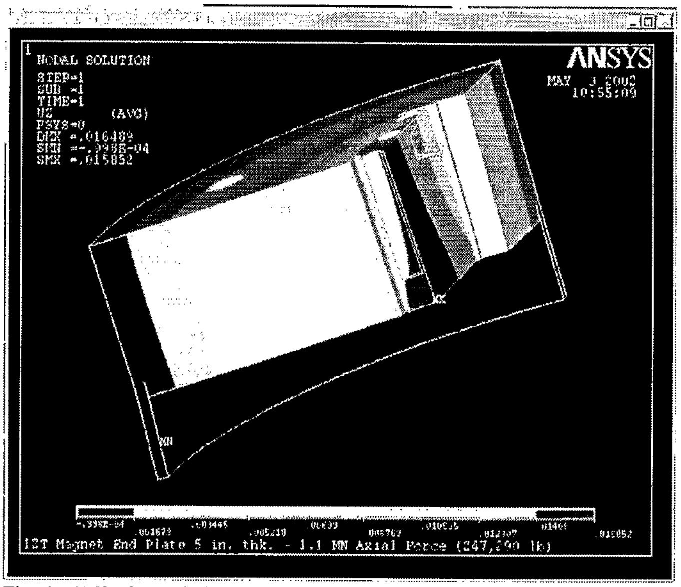

Fig. 4. ANSYS - end plate axial deflection - inches

IV. 12 T COMMON COIL TOOLING

In conjunction with the 12 T common coil magnet program, a new complement of tooling is required to complete the required assembly operations while handling the brittle superconductor in gentle fashion. The new equipment as described below is presently under construction.

A new cable insulating / re-spooling line is planned for use with both Nb_3Sn and HTS conductors of various configurations. This tool will control cable tension by connecting the pay-out and take-up spools to a load cell system, avoiding problems associated with monitoring the cable directly. Second, the uncertainty in cable position as it pays off of the spool will be actively corrected by photocells which sense cable position and activate motors to jog the spool position laterally to compensate, again providing control while minimizing flexing and direct handling of the cable.

A new winding machine will be utilized for all conductor types and configurations. In the new winder, cable will be tensioned without applying unnecessary flexure. In addition, the coil will shuttle back and forth while the spool translates laterally from a gantry that is fixed axially with respect to the coil [Fig. 5]. In this configuration, spool motion about coils of any length or width is coordinated such that no conductor re-spooling is required at successive turns during winding.

A second generation curing station, presently being built, utilizes many of the lessons learned with earlier tools, while reducing handling risks. It will be able to accommodate the Kevlar string/clamp arrangement of previous tools, while allowing for convenient and safe removal of clamps after the coil is securely placed in the potting fixture. It will feature a vacuum bag within a fixed cavity for reliability and repeatability, with versatility for molding coils of various widths and configurations. It will also feature a new array of clamps and slides, to permit safe installation of the coil into the tool.

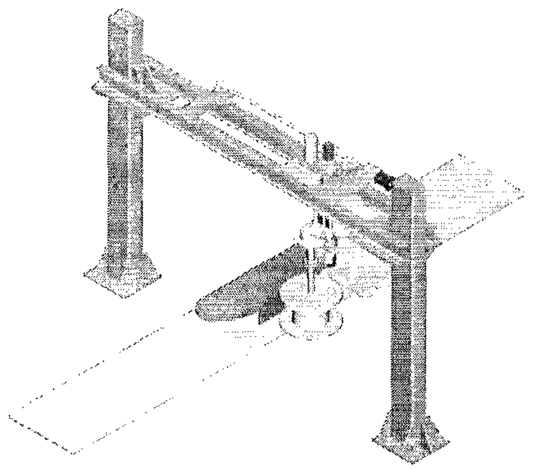

Fig. 5. Winding machine layout

V. RECENT TEST RESULTS

A recent hybrid magnet test successfully demonstrated many of the techniques that will be used in the construction of the 12 T magnet. Two 10-turn racetrack coils with a 300 mm-long straight section were wound from reacted 30-strand Nb_3Sn and vacuum impregnated. The conductor, from ITER stock, has J_c typically 650 A/mm^2 in the non-copper region (4.2 K, 12 T). The coils were assembled in the common coil configuration [6] with a single racetrack coil, wound with BSCCO-2212 [7] cable, placed between them. The HTS cable, designated #3, contained 18 strands, each 0.8 mm in diameter. At 4.5 K and 1 µV/cm, the cable had J_c = 320 A/mm^2 (4.2 K, zero field). The assembly preload on the coils was minimal, serving only to constrain them in all directions. Details of the magnet construction are given in [1].

The Nb_3Sn coils reached 11.9 kA, the estimated conductor limit, without training. With the Nb_3Sn coils off, the current in the HTS coils was increased until the coil voltage reached 1 µV/cm, at ~2 kA. This procedure was repeated with the Nb_3Sn coils at 3, 6, and 9 kA [Fig. 6]. The HTS coil was equipped with one voltage tap per turn in order to measure the uniformity of the material along its length. Despite the difference in field, the voltage gradient along each turn was almost the same. For all but one full turn, the gradient was the same within ± 5%. The voltage gradient was 25% higher in the turn nearest the pole.

VI. CONCLUSIONS

The 12 T magnet design, summarized herein, takes advantage of both well-established design features and newly developed technologies. Its designers foresee this type of high performance magnet being used in accelerators in the near future. The 10-turn coil test results are encouraging because many of the coil's construction features are carried over to the 12 T magnet. The coil tooling is specifically designed to handle the new characteristically fragile breed of high performance superconductors. When built, this magnet will

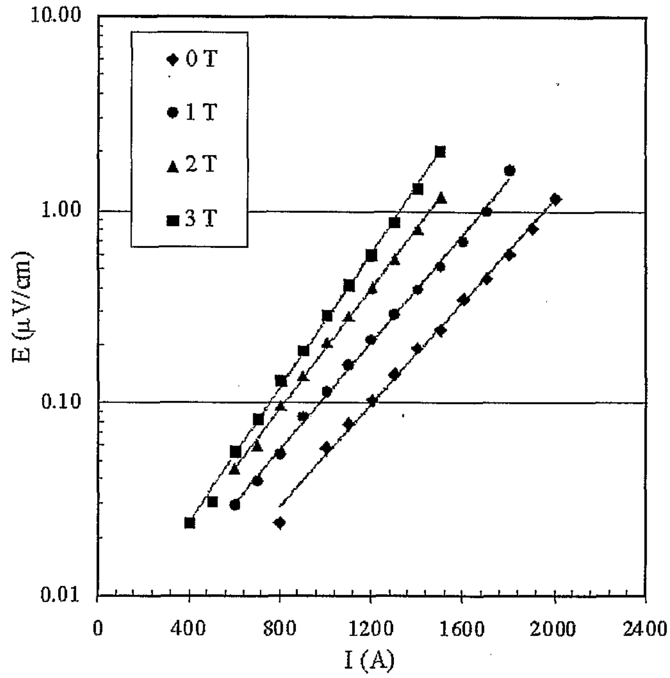

Fig. 6. Coil voltage as a function of current recorded for various current levels in the Nb_3Sn background coils.

serve two very useful purposes: to produce a very high background field for HTS conductor testing, and to be the prototype for future high performance accelerator magnets.

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